

The extinction curve in the visible and the value of R_V

Frederic Zagury^a

^aHarvard University, Cambridge, MA 02138

Abstract

This article discusses the interstellar extinction curve in the visible and the value of the ratio of absolute to selective extinction $R_V = A_V/E(B-V)$. It is concluded that the visible extinction curve is likely to be linear in the visible and that indirect estimates of R_V from tentative determinations of A_V or from infrared and UV observations are questionable. There is currently no evidence of any variation of R_V with direction. If R_V is close to 3, as it has been inferred from mid-infrared data, starlight in the visible is extinguished by a factor $F/F_0 = (2.5e^{-2\mu\text{m}/\lambda})^{E(B-V)}$. But if the visible wavelength range alone is considered, 4 appears as its most natural and probable value and $F/F_0 = e^{-2E(B-V)/\lambda}$.

Keywords: ISM: dust, extinction, galaxies: fundamental parameters

1. Introduction

Between 1937 and 1941 a series of papers specified the characteristics of interstellar extinction in the visible, provided a better understanding of the processes at work, and set the general frame-work for all forthcoming studies. Greenstein (1937, 1938) proved that extinction of a star's light in the visible was not of the Rayleigh type ($\propto e^{-a/\lambda^4}$) as previously thought¹, but was very close to a decaying exponential of $1/\lambda$ ($\propto e^{-a/\lambda}$, that is the visible extinction law was linear in $1/\lambda$). Such laws are common in nature (atmospheric aerosols, Fig. 1, are the best but not the only example), and attributed to size distributions of particles, with no specific implication on their chemical composition. These distributions are usually associated with large albedos and strong forward scattering phase functions, two properties which in the case of interstellar dust were confirmed in 1940 (Henyey & Greenstein 1940, 1941).

Linear extinction laws are defined by two parameters, their slope, proportional to the reddening $E(B-V) = A_B - A_V$ on the line of sight, and the extinction at a specific wavelength A_{λ_0} . The extinction at wavelength λ normalized by the reddening, $A_\lambda/E(B-V)$, depends on the absolute extinction to color excess ratio (R_V in the Johnson photometric system) alone (Sects. 2 and 3).

Greenstein found good spatial homogeneity of interstellar extinction. Assuming that the extinction law goes to 0 in the infrared (Stebbins, Huffer, & Whitford 1939) a value of $R_V = 4$ is obtained (see also Mendoza (1965)). In contrast Greenstein & Henyey (1941) found from a statistical analysis of the mean reddening at two different wavelengths that interstellar extinction becomes zero at $3.2 \mu\text{m}$, which implies $R_V = 3.3 (\pm 0.1)$.

Since the 1940s the debate on interstellar extinction has focused on four essential questions. How close to a perfect exponential is the extinction of starlight in the visible? Does extinction vary from direction to direction (from an interstellar cloud to another)? On how many parameters does it depend? How does it constrain the composition of interstellar dust?

The purpose of this paper is to evaluate which logical conclusions on interstellar extinction in the visible and the near-infrared ($4300 \text{ \AA} - 1.4 \mu\text{m}$) may be reached from an analysis of the abundant and often contradictory literature on the subject: what is the shape of the visible extinction curve? Is the key parameter R_V a constant or is it highly variable, as different studies separately claim, and what is its value(s)? Can extinction in the UV or in the infrared be related to the visible extinction and to the value of R_V ?

Sect. 2 gives the relevant definitions that are used in this paper. Sects. 3 to 5 review the main features of interstellar extinction in three wavelength domains which have been used to investigate the value of R_V , the visible, the infrared

¹The first hint for a $\lambda^{-\alpha}$, with α close to 1, wavelength dependence of interstellar extinction came from Hall (1937), in opposition to previous suggestions of a Rayleigh $1/\lambda^4$ extinction (Trumpler 1930; Stebbins & Whitford 1936).

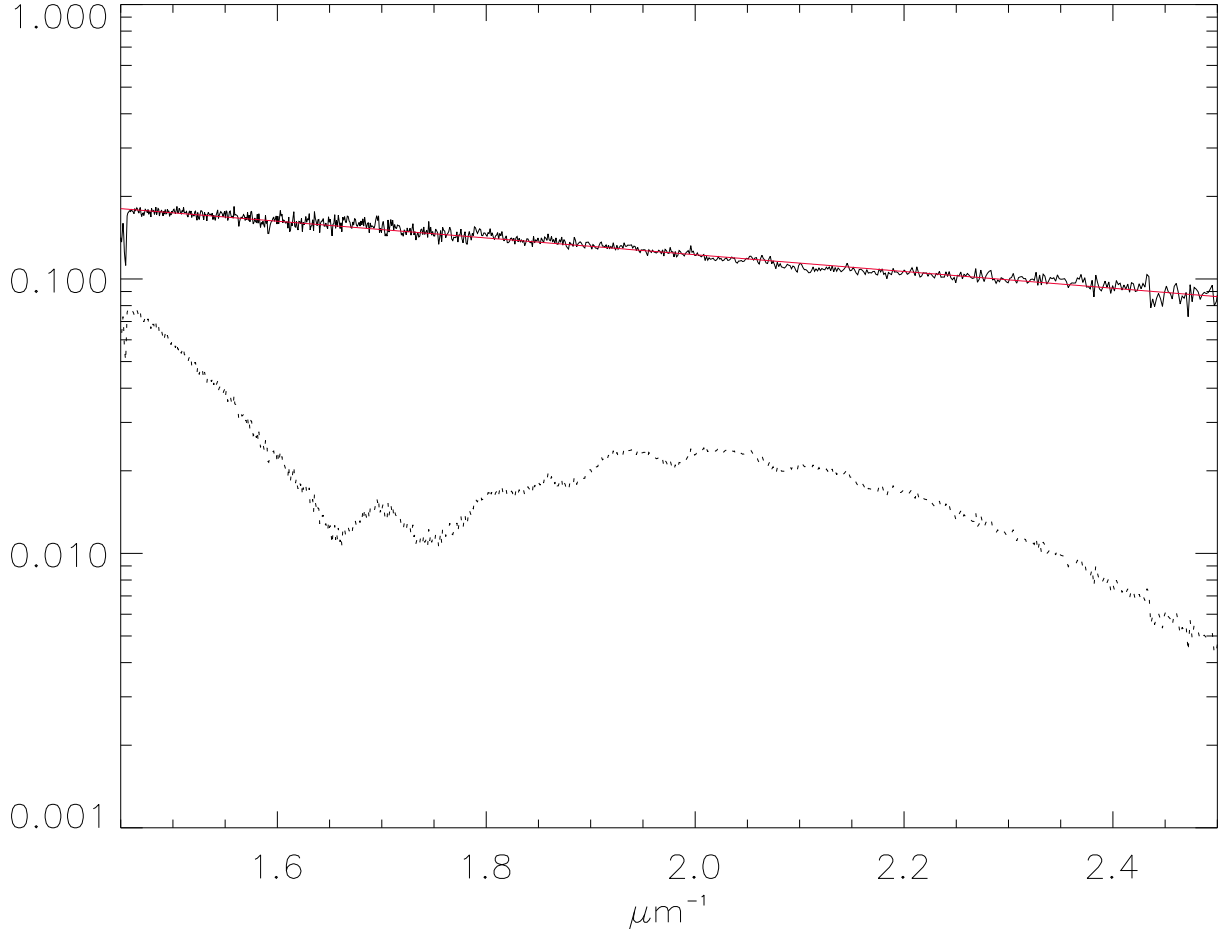


Figure 1: Night occultation of Sirius observed by satellite GOMOS. Bottom spectrum is the spectrum of Sirius observed at a tangent altitude of 14.8 km, normalized by the spectrum of Sirius outside the atmosphere. Top spectrum is the same after correction for ozone and Rayleigh (nitrogen) extinctions ($N_{O_3} = 3.7 \cdot 10^{20} \text{ cm}^{-2}$, $N_{N_2} = 1.2 \cdot 10^{17} \text{ cm}^{-2}$). Only aerosol extinction remains which behaves as an exponential of $1/\lambda$ (red trace, $\propto e^{-0.7/\lambda}$). Courtesy of Jean-Paul Bertaux and Laurent Blanot (Service d'Aéronomie, Verrières-le-Buisson, France).

(near and mid-infrared, $0.8\mu\text{m} \leq \lambda \leq 3\mu\text{m}$), and the UV. Sect. 6 questions the variability of R_V . Sect. 7 attempts to give the most logical responses to the questions raised in the previous paragraph.

2. Definitions

Let F_λ be the flux of a reddened star, measured on earth, and $F_{0,\lambda}$ that of an unreddened star of same spectral type. The quantity which is readily accessible through observation is the excess of extinction of the reddened star at wavelength λ over the extinction at a given wavelength λ_0 ,

$$A_\lambda - A_{\lambda_0} = E(\lambda - \lambda_0) = -2.5 \log \frac{\frac{F_\lambda}{F_{0,\lambda}}}{\frac{F_{\lambda_0}}{F_{0,\lambda_0}}} \quad (1)$$

Extinction in different directions can be normalized to the same amount of reddening between λ_0 and another given wavelength $\lambda_1 (< \lambda_0)$ by dividing $E(\lambda - \lambda_0)$ by $E(\lambda_1 - \lambda_0)$. Normalized extinction curves are defined by

$$g_{\lambda_1,\lambda_0}(1/\lambda) = \frac{E(\lambda - \lambda_0)}{E(\lambda_1 - \lambda_0)} = \frac{A_\lambda}{E(\lambda_1 - \lambda_0)} - R_{\lambda_1,\lambda_0} \quad (2)$$

with

$$R_{\lambda_1, \lambda_0} = \frac{A_{\lambda_0}}{E(\lambda_1 - \lambda_0)} \quad (3)$$

$g_{\lambda_1, \lambda_0}(1/\lambda)$ measures the extinction per unit amount of interstellar matter along the line of sight.

Normalized extinction curves g_{λ_1, λ_0} in different directions all pass through the points $(1/\lambda_0, 0)$ and $(1/\lambda_1, 1)$ in the $(1/\lambda, g_{\lambda_1, \lambda_0})$ plane, and have the same mean slope, $(\lambda_0^{-1} - \lambda_1^{-1})^{-1}$. For extinction to be the same in different directions normalized extinction curves need to be identical. In this case knowledge of $E(\lambda_1 - \lambda_0)$ fixes the amount of extinction and the quantity of interstellar dust on the line of sight at all wavelengths. If g_{λ_1, λ_0} varies with direction extinction depends on $E(B-V)$ and one or more additional parameters.

Two systems of normalization, (λ_3, λ_2) and (λ_1, λ_0) can be converted one into the other by

$$g_{\lambda_3, \lambda_2}(1/\lambda) = \frac{g_{\lambda_1, \lambda_0}(1/\lambda) - g_{\lambda_1, \lambda_0}(1/\lambda_2)}{g_{\lambda_1, \lambda_0}(1/\lambda_3) - g_{\lambda_1, \lambda_0}(1/\lambda_2)} \quad (4)$$

In Nandy's system (Nandy 1964), $1/\lambda_0 = 2.22 \mu\text{m}^{-1}$ and $1/\lambda_1 = 1.22 \mu\text{m}^{-1}$ were chosen to give a mean slope of unity. In the Johnson & Morgan (1953) photometric system ($1/\lambda_0 = 1/\lambda_V = 1.82 \mu\text{m}^{-1}$, $1/\lambda_1 = 1/\lambda_B = 2.27 \mu\text{m}^{-1}$) the slope is 2.22, and normalized extinction curves are defined by

$$g_0(1/\lambda) = \frac{A_\lambda}{E(B-V)} - R_V \quad (5)$$

with

$$R_V = \frac{A_V}{E(B-V)} = \frac{1}{\frac{\sigma_B}{\sigma_V} - 1} \quad (6)$$

σ_B and σ_V are the extinction cross-sections of interstellar dust in the B and V bands in the direction of the observation.

Eq. 5 emphasizes the importance of R_V . If R_V is known, A_λ becomes measurable at all wavelengths. Eq. 6 shows that R_V depends only on the extinction properties of interstellar dust in the B and V bands (along the line of sight). Identical normalized extinction curves in different directions certainly imply equality of R_V in these directions.

The constancy or not of R_V and its exact value(s) determine our ability to evaluate A_λ in any direction, to correct observations of far-away objects for foreground reddening, and to parametrize interstellar dust models. The Schlegel, Finkbeiner, & Davis (1998) derivation of A_λ in different photometric bands from $E(B-V)$ for instance relies on the assumption that R_V is constant and equal to 3.1; their estimate of interstellar extinction in any direction is widely used today.

There is no direct and straightforward way to estimate R_V . $E(B-V)$ is deduced from a star spectral type and flux ratio between the B and V bands but A_V can not be ascertained unless the star absolute luminosity and distance are precisely known. Existing determinations of R_V rely on indirect methods, the extension of g_0 to the infrared (Sect. 4), estimates of A_V , or on the UV extinction curve (Sect. 6).

3. The visible extinction curve

With the exception of Divan's work (Divan 1954) spectral studies of interstellar extinction in the visible are rare. There is a lack of a large, reliable data-base of stellar spectra free from atmospheric extinction, such as exists in the UV (the IUE data-base). Spectra in analytical form did not become common before the 1950-1960s and a precise removal of atmospheric extinction (which also has a dependence on $1/\lambda$, Fig. 1) is not obvious. Photometry, sometimes from only a few data-points, has been the standard means to study extinction in the visible, although it is less accurate than spectral analysis can be.

The upper plot of Fig. 2 is the ratio F/F_0 , in the [1250, 8000] wavelength range, for the star HD46223². With an excellent precision the visible part of the spectrum follows a decaying exponential of $1/\lambda$ (and diverges from it in the UV).

²observations from J.F. Le Borgne library of stellar spectra, <http://www.ast.obs-mip.fr/article181.html> Le Borgne (2003)

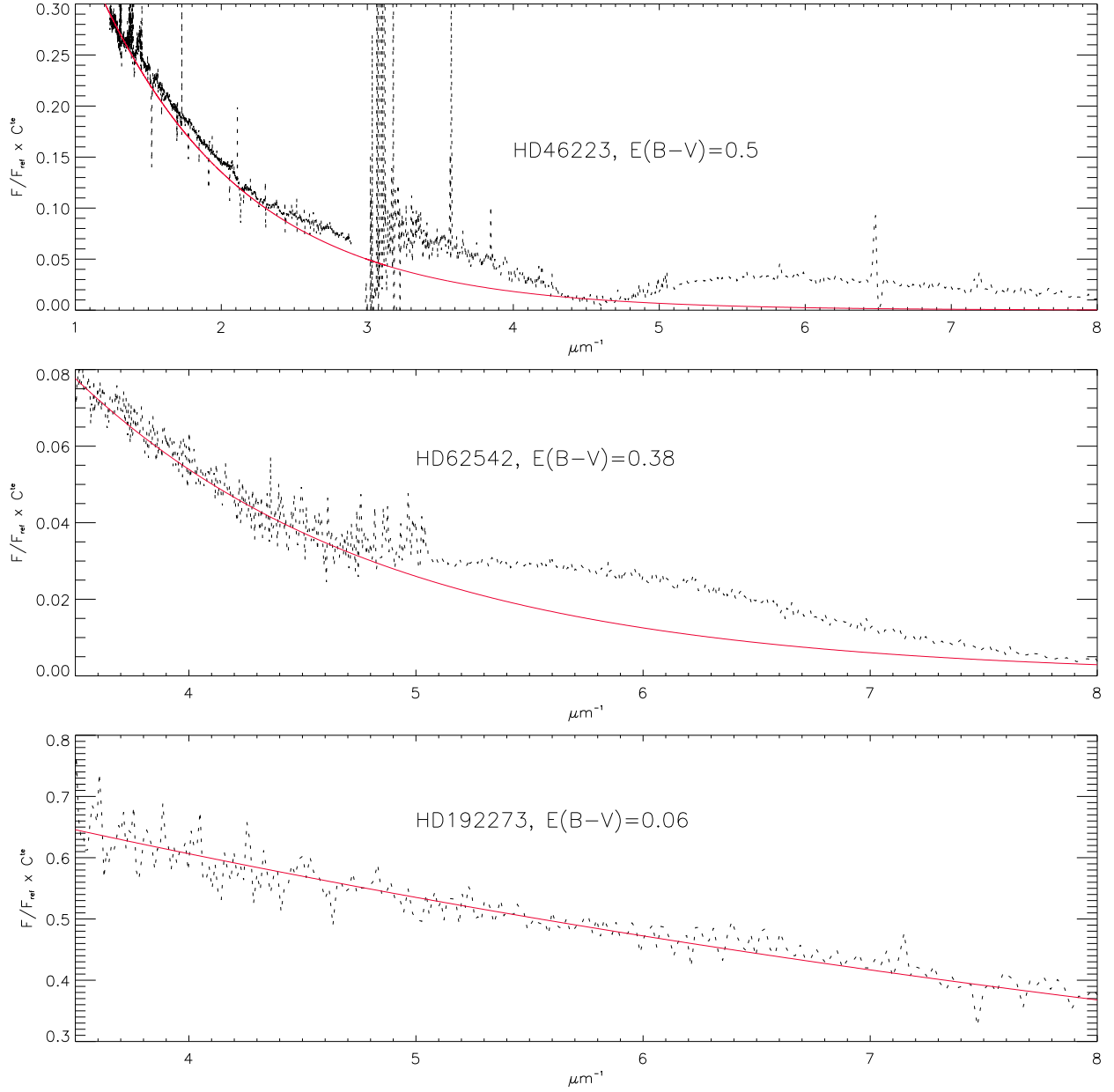


Figure 2: Extinction of HD46223, HD62542, HD192273. From top to bottom, ratios of the spectra of HD46223 to the unreddened star of same type HD269698 (15 Mon), of HD62542 to HD32630, of HD192273 to HD31726. The red lines are the exponentials $e^{-2\Delta(B-V)/\lambda}$, with $\Delta(B-V)$ the B-V difference between the reddened and the reference stars. The extinction of HD192273 is linear throughout the visible-UV wavelength range, in the visible to the near-UV for HD62542, and in the visible only for HD46223. The F/F_0 ratios have been normalized so that the fits be exactly $e^{-2\Delta(B-V)/\lambda}$ (which implies $R_V = 4$, Sect. 7).

This exponential decrease of the extinction of starlight in the visible is confirmed by most studies³ of visible normalized extinction curves. Divan (1954), Whitford (1958), Nandy (1964), Ardeberg & Virdefors (1982) and more recently Bondar et al. (2006) found the same $g_{\lambda_1, \lambda_0}(1/\lambda)$ in all directions (over the visible domain).

The most extensive data-set of extinction curves in the visible was gathered by Nandy in the 1960-1970s (see review, Wickramasinghe (1998)). The extinction curve weighted over a large number of observations that he derived in 1964 (Nandy 1964) is reproduced in Fig. 3. It is to a high degree of accuracy linear in the visible from $2.3 \mu\text{m}^{-1}$ (4350 Å) to $0.8 \mu\text{m}^{-1}$ ($1.2 \mu\text{m}$) in the near-infrared (Wickramasinghe 1998; Whitford 1958). In this wavelength range the exponential dependence of $F_\lambda/F_{0,\lambda}$ can equally be expressed as

$$\frac{F_\lambda}{F_{0,\lambda}} = C_0 e^{-a/\lambda} = e^{-(a/\lambda+b)} \quad (7)$$

or by

$$\begin{aligned} A_\lambda &= \frac{(A_B - A_V)}{\frac{1}{\lambda_B} - \frac{1}{\lambda_V}} \left(\frac{1}{\lambda} - \frac{1}{\lambda_V} \right) + A_V \\ &= 2.22E(B - V) \left(\frac{1 \mu\text{m}}{\lambda} + 0.46(R_V - 4) \right) \end{aligned} \quad (8)$$

From Eqs. 7 and 8

$$a = 2.02E(B - V) \quad (9)$$

$$b = 0.92E(B - V) \times (R_V - 4) \quad (10)$$

The extinction per unit reddening is

$$\frac{A_\lambda}{E(B - V)} = 2.2 \left(\frac{1 \mu\text{m}}{\lambda} + 0.46(R_V - 4) \right) \quad (11)$$

$$g_0(\lambda) = \frac{2.2 \mu\text{m}}{\lambda} - 4 \quad (12)$$

$$\left(\frac{F_\lambda}{F_{0,\lambda}} \right)_{E(B-V)=1} = e^{-0.92(R_V-4)} e^{-2\mu\text{m}/\lambda} \quad (13)$$

4. The infrared extinction curve

Observed extinction curves are linear only in the visible and part of the near-infrared domain. Fig. 3 shows that the curve deviates in the near-UV above $1/\lambda \sim 2.3 \mu\text{m}^{-1}$ (shortly after the B -band) where there is less extinction than expected. The error margin on Fig. 3 increases dramatically because extinction in the UV no longer depends on $E(B - V)$ alone (Sect. 5).

In the infrared extinction is much less than at shorter wavelengths. Error margins are large and the extinction curve is difficult to ascertain. Infrared extinction data are limited to a few photometric bands, and thermal emission from dust grains shows up above a few μm (Sherwood (1975) and references therein). Below $0.8 \mu\text{m}^{-1}$ published mid-infrared extinction laws do not follow the visible law (Stead & Hoare (2009), figs. 1 and 2 in Whitford (1958), fig. 2 in Ardeberg & Virdefors (1982)). The extinction curve seems to flatten shortward of $1/\lambda \sim 0.8 \mu\text{m}^{-1}$ ($1.2 \mu\text{m}$) and extinction may be larger than predicted by the linear behavior in the visible.

Mid-infrared extinction was used (Johnson 1965, 1968; Wegner 2003) to probe variations of R_V ($g_0(1/\lambda \rightarrow 0) \rightarrow -R_V$, Eq. 5). These findings are contradicted by several studies (Bondar et al. 2006; Sherwood 1975; Rozis-Saulgeot 1956; Schalén 1975; Schultz 1975), sometimes even in the same regions of the sky. There is today no tangible proof of spatial variations of the extinction in the infrared. The legitimacy of using the infrared to determine R_V is also questionable, especially with respect to the spatial constancy of $g_0(\lambda)$ in the visible wavelength range (Sect. 7 and Mendoza (1965)).

³two notable exceptions are the photometric observations of Johnson (fig. 12 in Johnson (1965)) and of Schild (1977) who finds that 'in no octave of the spectrum is the interstellar absorption strictly proportional to reciprocal wavelength.....it is becoming increasingly clear that variations with Galactic longitude are important' (see also Borgman (1954); Johnson & Morgan (1955); Johnson (1968)). Johnson's observations and methods (especially his summary in Johnson (1968)) are criticized in several articles (Sherwood 1975; Rozis-Saulgeot 1956; Schalén 1975; Schultz 1975).

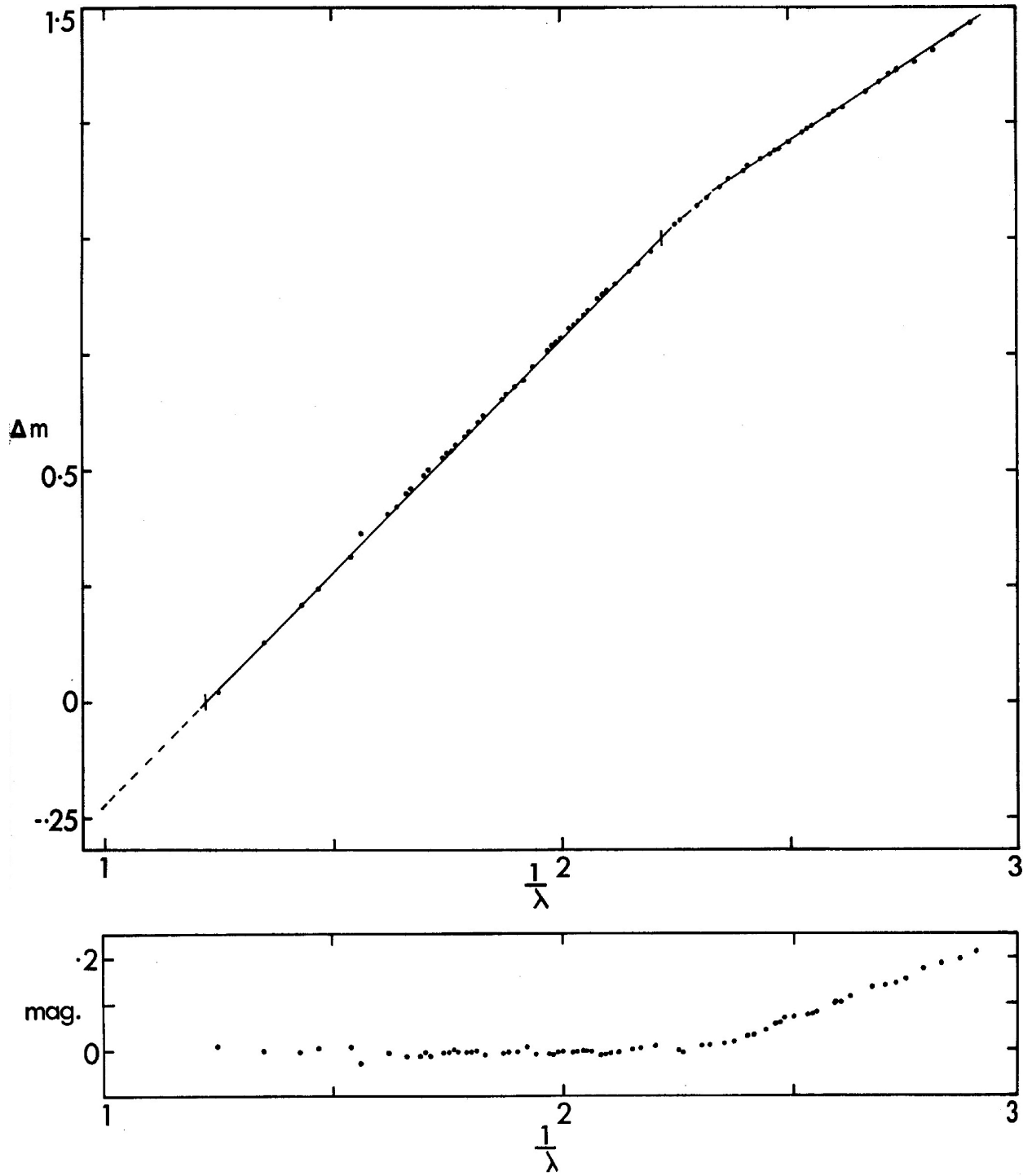


Figure 3: The visible normalized extinction curve (top) derived by K. Nandy, and the error margin (figs 14 and 15 in Nandy (1964)). The curve is linear down to $1/\lambda \sim 0.8 \mu\text{m}^{-1}$ ($\lambda \sim 1.2 \mu\text{m}$, see figs. 1 and 2 in Whitford (1958), fig. 5 in Hoyle & Wickramasinghe (1969), and fig. 2 in Ardeberg & Virdefors (1982)).

5. The UV extinction curve

The UV extinction curve exhibits the well-known 2200 bump feature (upper plot of Fig. 2); the extinction is less than expected from the continuation of the visible extinction curve (Figs. 2). Early in the 1970s it was recognized that normalized $g_0(1/\lambda)$ curves depend on direction: $E(B - V)$ alone is not enough to determine the whole extinction curve. These properties have largely contributed to the development of new interstellar dust models (see Hoyle & Wickramasinghe (1991)).

Cardelli, Clayton, & Mathis (1989) (CCM in the following) proved in 1989 that most normalized curves with a bump can be deduced from a function of $1/\lambda$ which depends upon a single parameter, R_{ccm} . In the CCM framework the size of the bump depends on $E(B - V)$ only (this is a crude approximation, see Savage (1975)) while the free parameter determines the average slope of the extinction curve (with respect to the one in the visible) and its shape in the far-UV. Cardelli, Clayton, & Mathis (1989) assume that R_{ccm} is equal to R_V , an affirmation to be discussed in Sect. 6.

Cases also exist where the linear visible extinction extends to the near-UV, eventually to the far-UV (Fig. 2). A linear extinction curve over all the visible-UV can be found in the directions of very low column density within the Galaxy (Fig. 2, bottom plot, and Zagury (2001)); similar extinction curves are observed in the Magellanic Clouds along lines of sight with even higher column density (Zagury 2007). In some directions, HD62542 (Fig. 2, middle plot) or HD29647 in our Galaxy, Sk-69228 and Sk-70116 in the LMC (Zagury 2007), the extinction is linear down to the bump region and diverges from linearity in the far-UV only. All these directions have no bump and cannot be fitted by the CCM function. The CCM fit can be improved to include linear extinction curves (Zagury 2007).

6. On the variations of R_V

If, in the visible, normalized extinction curves $g_0(1/\lambda)$ do not depend on direction (Sect. 3) there is no reason why the relative extinction cross-sections of interstellar grains in the R and B bands (Eq. 6) should vary, and R_V should remain constant (Sect. 2).

Paradoxically the constancy of R_V is disputed not so much from the study of interstellar extinction in the visible itself but from indirect and generally more speculative methods, which often involve the extinction in other wavelength ranges. They rely either on infrared data (which are not conclusive, Sect. 4); on tentative estimates of A_V ; or on the CCM fit of UV extinction curves (Sect. 5).

Direct determination of A_V uses star count methods or open clusters distance estimates. Star counts for the same region have resulted to contradictory conclusions regarding the nature and variability of R_V (Johnson 1968; Schallén 1975; Balázs et al. 2004). The values of R_V range from 3 to 6 (Balázs et al. 2004). Distance estimates of open clusters are no more convincing. In a recent article Turner (2011) shows that the distance to open cluster Shorlin 1 should be revised from over 10 kpc to less than 3 kpc and thereby demonstrates the large errors which are associated to distance estimates by means of photometry. The same paper also lists some thirty determinations of R_V in the Carina region which range from 3 to 5.2. Such variations over a small area of the sky are obviously difficult to reconcile with the constancy of g_0 found by Nandy, Divan, Bondar, and others (Sect. 3).

The same remark applies to the UV. The use (since 1989) of the CCM fit to probe large and local variations of R_V is questionable. The free parameter R_{ccm} of an extinction curve is obtained from eq. 1 in CCM

$$\frac{A_\lambda}{A_V} = a(x) + \frac{b(x)}{R_{ccm}}, \quad (14)$$

where $a(x)$ and $b(x)$ are functions of $x = \lambda^{-1}$ alone (Cardelli, Clayton, & Mathis 1989). For the B band ($x_B = 2.27\mu\text{m}^{-1}$) Eq. 14 yields, in any direction

$$\frac{A_B}{A_V} = a(x_B) + \frac{b(x_B)}{R_{ccm}},$$

or

$$\frac{1}{R_V} = a(x_B) - 1 + \frac{b(x_B)}{R_{ccm}}$$

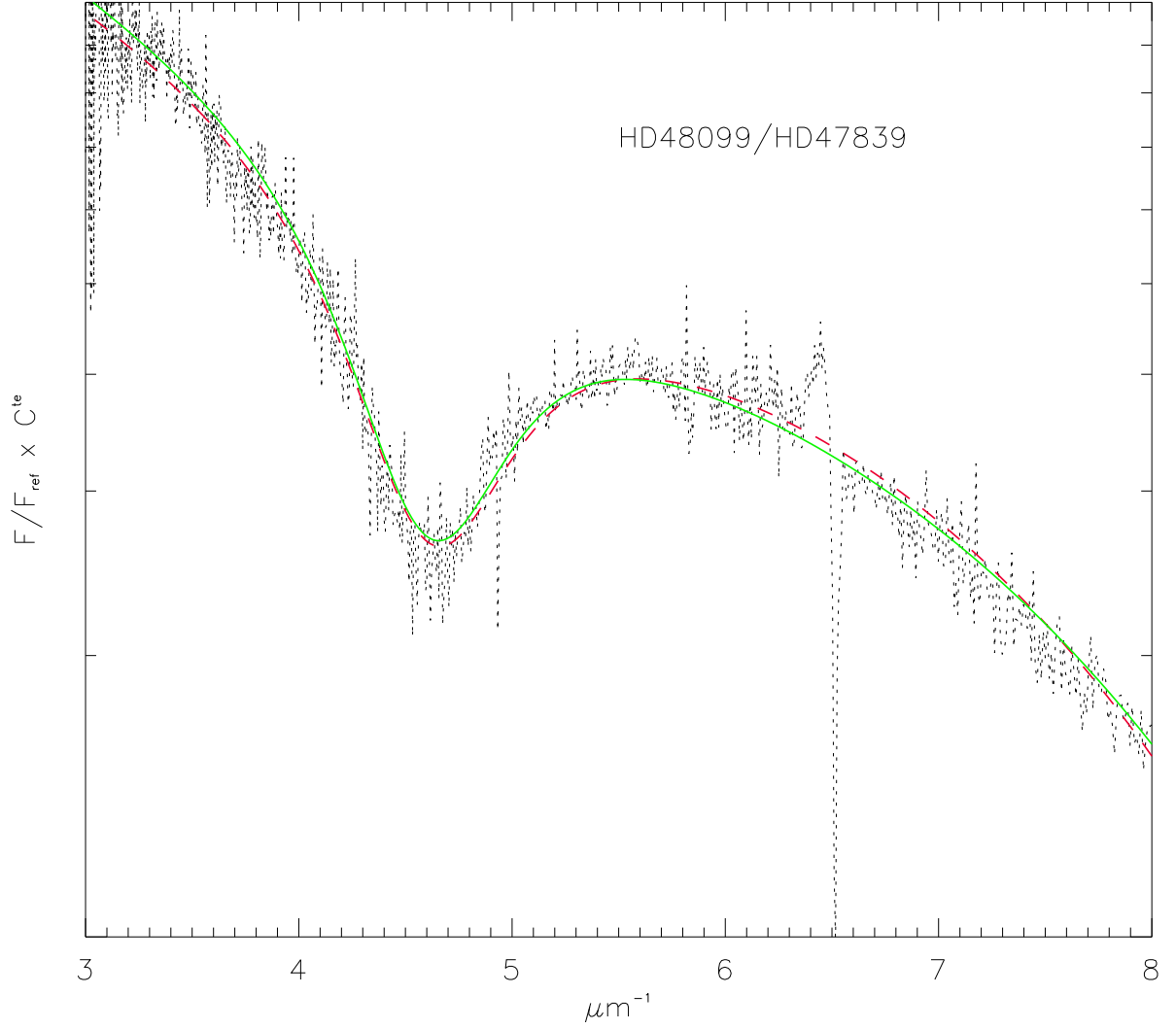


Figure 4: Dotted spectrum is the ratio of HD48099 (reddened star) to the slightly reddened ($E(B - V) = 0.07$) star HD47839, corrected for extinction. If the slight reddening ($E(B - V) = 0.07$) of HD47839 is considered, the CCM fit is the red dashed spectrum, with free parameter $R_{ccm} = 1.2$. If half only of this reddening is corrected, the CCM fit is the green spectrum, with $R_{ccm} = 3.4$, close to the value found in Cardelli, Clayton, & Mathis (1989). A slight error in the adopted value of $E(B - V)$ can thus lead to largely different values of the CCM free parameter. The plot also shows that R_{ccm} has no impact on the size of the bump, which, in the CCM framework, is controlled by the reddening $E(B - V)$.

If $R_{ccm} = R_V$

$$R_V = -\frac{1 - b(x_B)}{1 - a(x_B)}. \quad (15)$$

Should R_{ccm} be equal to R_V Eq. 15 shows that it would have to be a constant (from Eq. 15 and eqs. 3a and 3b in CCM: $R_V = 1.48$) independent of direction. This is in contradiction with the fact that the free parameter of the CCM parameterization, R_{ccm} , varies according to direction. R_V is therefore unlikely to be the free parameter of the CCM function.

It is further difficult to conceive how R_{ccm} , which in practice fixes the average UV slope of the CCM fit with respect to the mean slope of $g_0(1/\lambda)$ in the visible (fig. 4 in Cardelli, Clayton, & Mathis (1989) and Zagury (2007)), can influence the visible extinction curve, let alone R_V . It also should be noted that the parameter R_{ccm} is highly sensitive to the estimated value of $E(B - V)$ (Fig. 4), and is not necessarily the same whether the CCM law or its improved formulation in Zagury (2007) are employed. Last, R_{ccm} barely agrees with the value of R_V derived by other methods, which find, using similar data-sets, either different values in the same region (in the Magellanic Clouds for instance (Zagury 2007)) or a constant R_V (Bondar et al. 2006; Schlafly et al. 2010).

7. Discussion

The interstellar extinction curve is now accessible through the entire spectrum although studies in each of the three wavelength regions (the infrared, the visible, and the UV) are generally done separately and rely on observations with different quality, sensitivity, and resolution. In the infrared there is no conclusive evidence that interstellar extinction should depend on another parameter in addition to $E(B - V)$ (Sect. 4 and Sherwood (1975)).

Extinction in the UV, although the best documented, remains to be understood. The Cardelli, Clayton, & Mathis (1989) paper had a strong impact and was a remarkable breakthrough. It proved that interstellar extinction in the UV depends on $E(B - V)$ and on an additional parameter only. The CCM function, representative of normalized extinction curves with a bump at 2200, is however purely empirical and void of physical significance. Its free parameter is unlikely to be R_V (Sect. 6). The nature of the parameter which governs UV extinction is still to be determined.

Over sixty years of observations support a linear extinction law in the visible, with $g_0(1/\lambda)$ normalized extinction curves independent of direction (Sect. 3). Linear extinction laws are attributed to grain size distributions ($\Phi(a)da = a^{-4}da$ in van de Hulst (1981)). They have no implication for the chemical composition of the grains responsible for the extinction: extinction by aerosols in the atmosphere, like interstellar dust, follows a similar law. The extinction at a specific wavelength is due to particles of size close to the wavelength.

The spatial uniformity of $g_0(1/\lambda)$ in the visible strongly favors a constant value of R_V (Sect. 2). Estimates of A_V in different directions, which essentially are of a statistical character (Balázs et al. (2004) and Sect. 4), suggest that R_V should be between 3 and 6.

The flattening of the extinction curve observed in the near-infrared (fig. 2 in Whitford (1958)), which interrupts the linear decrease of $g_0(1/\lambda)$ towards the longest wavelengths, was used to derive a value of R_V close to 3. If R_V is indeed close to 3, Eq. 13 may be rewritten as

$$\left(\frac{F_\lambda}{F_{0,\lambda}} \right)_{E(B-V)=1} = 2.5e^{-2\mu_m/\lambda} \quad (16)$$

It is however arbitrary to determine R_V from infrared data since below $0.8 \mu\text{m}^{-1}$ the interstellar extinction curve seems not to follow the same analytical law as in the visible. R_V should depend on the distribution of those interstellar dust grains with sizes close to λ_B and λ_V and be determined from the extension to longer wavelengths of $A_\lambda/E(B - V)$ rather than from the observed mid-infrared data. The mid-infrared flattening, should it be confirmed, may as well result from a process independent from the extinction at shorter wavelengths, from a change in grain-size distribution for the largest interstellar grains for instance.

A general difficulty in discussing these estimates of R_V is that R_V can be defined in different ways which do not necessarily have the same meaning. The exact definition, $R_V = A_V/E(B - V)$, involves only the reddening in the B and V bands. Because direct determination of these quantities is particularly difficult alternative definitions rely on the limit of $g_0(1/\lambda \rightarrow 0)$, and on the supposition that $A_\lambda(1/\lambda \rightarrow 0) \rightarrow 0$ which is true only if there is no gray (neutral)

extinction. But the $g_0(1/\lambda \rightarrow 0)$ limit can also be considered in two ways, either by taking the limit of mid-infrared observations, as it is generally done, or by continuing Nandy's linear extinction law (Fig. 3) to the longer wavelengths.

As stated above the infrared method, which leads to $(R_V)_{IR} \approx 3$ and to Eq. 16, is not consistent with the original definition of R_V . If there is a flattening of the extinction in the near-infrared $(R_V)_{IR}$ must be smaller than $A_V/E(B-V)$ and underestimates R_V .

If Nandy's curve in the visible alone is considered, provided that the B -band lies within the limits of the linear part of normalized extinction curves (that is, if A_B is not or little affected by the near-UV departure from linearity, Fig. 3), and assuming no gray extinction, Eqs. 5 and 12 necessarily imply $R_V = 4$. This conclusion can be re-formulated in the following way. If linear normalized extinction curves in the visible were to be considered alone one would expect, from any size distribution of particles, that the coefficient in front of the exponential in Eq. 16 be less than 1 (instead of 2.5). In absence of neutral extinction, which is presumed to be the case for interstellar dust (Dufay 1954; Sherwood 1975), this coefficient, C_0 in Eq. 7 (or $e^{-0.92(R_V-4)}$ in Eq. 13), should be 1. Then

$$\frac{F_\lambda}{F_{0,\lambda}} = e^{-\frac{2\mu\text{m}}{\lambda}E(B-V)} \quad (17)$$

$$\frac{A_\lambda}{E(B-V)} = \frac{2.2\mu\text{m}}{\lambda} \quad (18)$$

$$R_V = 4 \quad (19)$$

$R_V = 4$ is precisely the value Turner (2011) has obtained from his most recent photometric measurements in the Carina region. This value is not "anomalous" as it was often suggested, but rather appears as a logical outcome of the linearity of interstellar extinction in the visible.

This paper was motivated by the large and logically incompatible discrepancies that appear from a survey of the existing literature on the determination of R_V . Depending on the study R_V has been found to be either constant and independent of the line of sight or highly variable from one direction to another.

It is my conclusion that the normalized visible extinction law is most likely linear and independent of direction so that R_V should be the same constant for all directions. Although a value close to 3 is generally preferred, $R_V = 4$ would more naturally fit with the linear extinction law found in the visible.

Acknowledgments

This work was funded by an Arthur Sachs fellowship. I am grateful for the hospitality and resources provided by Harvard University.

References

- Ardeberg A., Virdefors B.: 1982, A&A, 115, 347
- Balázs L.G., Abrahám P., Kun M., Kelemen J., Tóth L.V.: 2004, A&A, 425, 133
- Bondar A., Galazutdinov G.A., Patriarchi P., Krelowski J.: 2006, JKAS, 39, 73
- Borgman J.: 1954, BAIN, 12, 201
- Cardelli J.A., Clayton G.C., Mathis J.S.: ApJ 1989; 345, 245 (CCM)
- Divan L.: 1954, AnAp, 17, 456
- Dufay J.: 1954, Nébuleuses galactiques et matiere interstellare, Editions Albin Michel, collection Sciences d'Aujourd'hui, Paris, p. 209
- Greenstein J.L.: 1937, HarCir, 422, 1
- Greenstein J.L.: 1938, ApJ, 87, 151
- Greenstein J.L., Henyey L.G.: 1941, ApJ, 93, 327
- Hall J.S.: 1937, ApJ, 85, 145
- Henyey L.G., Greenstein J.L.: 1940, AnAp, 3, 117
- Henyey L.G., Greenstein J.L.: 1941, ApJ, 93, 70
- Hoyle F., Wickramasinghe N.C.: 1969, Nature, 223, 459
- Hoyle F., Wickramasinghe N.C.: 1991, The Theory of Cosmic Grains, Kluwer Academic Publishers, Dordrecht
- Johnson H.L.: 1965, ApJ, 141, 923
- Johnson H.L.: 1968, in Middlehurst B.M., Aller L.H., eds, Nebulae and interstellar matter, Chicago, University of Chicago Press
- Johnson H.L., Morgan W.W.: 1953, ApJ, 117, 313
- Johnson H.L., Morgan W.W.: 1955, ApJ, 122, 142
- Le Borgne J.F., et al.: 2003, A&A, 402, 433

Mendoza E.E.: 1965, BOTT, 4, 3
 Nandy K.: 1964, Pub Roy. Obs. Ed., 3, 142
 Rozis-Saulgeot A.M.: 1956, AnAp, 19, 274
 Savage B.D.: 1975, ApJ, 199, 92
 Schalén C.: 1975, A&A, 42, 251
 Schild R.E.: 1977, AJ, 82, 337
 Schlafly E., et al.: 2010, ApJ, 725, 175
 Schlegel D.J., Finkbeiner D.P., Davis M.A.: 1998, ApJ, 500, 525
 Schultz G.V., Wiemer W.: 1975, A&A, 43, 133
 Sherwood W.A.: 1975, Ap&SS, 34, 3
 Stead J.J., Hoare M.G.: 2009 MNRAS, 400, 731
 Stebbins J., Whitford A.E.: 1936, ApJ, 84, 132
 Stebbins J., Huffer C.M., Whitford A.E.: 1939, ApJ, 90, 209
 Trumpler R.J.: 1930, PASP, 42, 214
 Turner D.G.: 2012, Ap&SS, 337, 303
 van de Hulst H.C.: 1981, Light scattering by small particles. Dover, NY
 Wegner W.: 2003, AN, 324, 219
 Whitford A.E.: 1958, AJ, 63, 201
 Wickramasinghe N.C.: 1998, Obs, 118, 398
 Zagury F.: 2001 NA, 6, 471
 Zagury F.: 2007, Ap&SS, 312, 113